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# The role and challenges of Rare Earths in the Energy Transition

Lisa DEPRAITER\* and Stéphane GOUTTE†

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## Abstract

The energy transition from fossil fuel energy to low-carbon energy is mineral intensive. Among the required minerals rare earth elements (REEs) are core components of clean energy technologies such as wind turbines and electric vehicles. This article focuses on the relationship between rare earth elements and the energy transition, while discussing demand and supply of these critical minerals in the energy transition process. We investigate the challenges regarding current and future supply of REEs for low-carbon technologies. The stakes and challenges are numerous between the Chinese quasi-monopoly, the absence of equivalent substitutes, the low recycling rates or even the environmental damage linked to the extraction and the production process. In the face of these issues, we propose concrete recommendations and policies in order to meet the ecological challenge of the energy transition and to ensure a reliable future supply.

**Keywords:** Rare Earths; Energy Transition; Supply; Renewable; Wind turbines; Electric Vehicles; China; Environment

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# 1 Introduction

In the global development of low-carbon energy to achieve emission reduction targets, minerals are seen as the vitamins to the energy transition. The criticality of raw materials has become a common issue in planning the transition from fossil fuel energy to low-carbon energy. The past decade has seen several countries establish critical raw materials lists, including minerals critical to the development of low-carbon energy. Among those minerals, rare earth elements have received a lot of attention. Rare earth elements (hereinafter referred to as REEs) are a group of 17 chemical elements, including 15 lanthanides (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium) and scandium and yttrium. REEs are grouped into one family of elements due to their chemical similarities. Rare earths are divided into two sub-categories : light rare earths (cerium, lanthanum, praseodymium, neodymium, promethium, europium, gadolinium and samarium), and heavy rare earths (dysprosium, yttrium, terbium, holmium, erbium, thulium, ytterbium, lutetium and scandium). There has been an increasing interest in rare earth elements due to their use in many advanced technologies, including low-carbon technology, mainly in wind turbine generators and electric vehicle motors. REEs are principally produced in China, and its political management of the resource has been the focus of several geopolitical studies [58, 57, 41, 74, 80] highlighting the criticality of the minerals. In addition, forecasting studies have drawn attention to the availability risks of main REEs used for wind turbines and electric vehicles, and more generally, the challenges surrounding rare earth elements supply [84, 83, 69]. Despite this large literature, few articles focus on the challenges of rare earth in the energy transition concerning supply and demand. This paper will focus on examining the role of rare earth elements in the energy transition and discuss the induced challenges while identifying policy recommendations. First, this paper gives a brief overview of REEs in the literature, the second section will focus on the REEs market, examining its characteristics, and finally, the last section will define the four main challenges identified: diversification, substitution, recycling and environmental and social concerns regarding rare earths mining to ensure a reliable future supply.

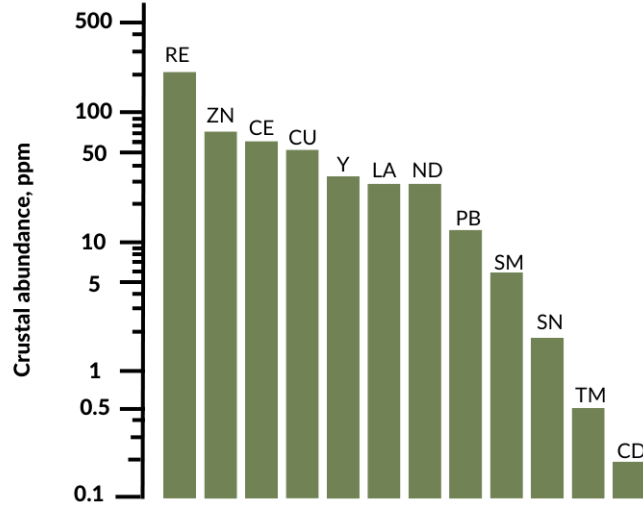


Figure 1: Mineral reserve abundance. Source: Gupta et al., 1992

## 2 Literature review

### 2.1 REEs occurrence, distribution and geology

There is an extended literature on rare earths occurrence, distribution, and geology [34, 26, 9, 20]. As explained by [34], despite their denomination REEs are not particularly rare in their crustal abundance concentration compared to regular metals such as zinc and copper. Crustal abundance concentration also varies among rare earth elements, the most abundant cerium and the least thulium. Unlike regular minerals, rare earths do not occur as individual minerals; hence rare earth minerals contain all REEs, with some enriched and others in low concentration [34]. The consequence, as highlighted by several papers [77, 32], is that the unequal repartition distribution of REEs compromises the isolation and recovery of individual REEs, which results in their unequal availability. Globally, rare earths rarely occur in concentrated and economically exploitable mineral deposits. As shown by [48] REEs deposits are located in the interior and marginal regions of continents, including Inner Mongolia, East African rift zones, northern Scandinavia-Kola peninsula, Eastern Canada, Southern Brazil and Southern China.[9, 34] state that overall there are 250 minerals identified as containing REEs, but only a dozen are considered resources for commercial extraction. According to [34, 26], the most common rare earth minerals and the principal economic source of REEs are Monazite, Bastnaesite, Xenotime and Ion-adsorption clay. Others include Euxenite, Apatite, Gadolinite, Laporite, Uraninite,

Brannerite, Doverite, Pyrochlore, Allanite, Perovskite, Zircon.

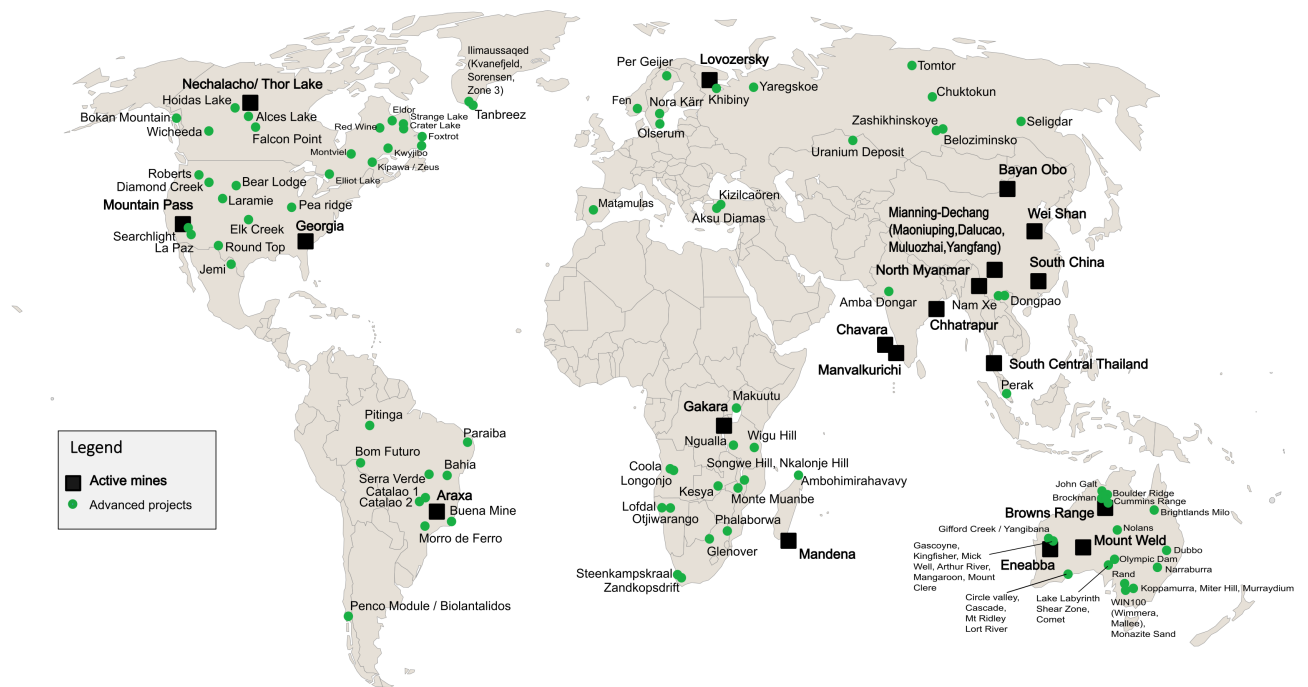


Figure 2: Current global distribution of REE projects, including both active mines and advanced projects. Sources: Adapted from Liu and al. 2023

Figure 2 represents the Global REE distribution, including active mines and advanced projects. The three major deposits include Bayan Obo (China), Mountain Pass (USA) and Mount Weld (Australia). Bayan Obo deposit is located northwest of Baotou, a northern China industrial region, in the Inner Mongol Autonomous Province [48, 20]. The Mountain Pass deposit, located in the Mojave Desert of California, is the second-largest deposit in the world and the only REE-mine in the United States [20]. Mount Weld comprises four deposits, the main REEs mineral being monazite. This deposit is enriched in heavy rare earths [20, 21], and it's the only heavy rare earths mine outside China. Another important resource of REEs outlined by [76, 91] is the ion adsorption clay deposit that stretches along seven provinces in southern China. The easy extractability of rare earths, and notably heavy rare earths, from this deposit makes it more economically viable compared to others. Rare earth can be retrieved from the surface clay with a few mining separation processes. Between 1988 and 2008, this deposit accounted for 26% of China's REEs production [76]. According to [16], the global reserve of rare earth is estimated at 120 million metric tons. China owns the largest reserve with 44 million metric tons, followed by Vietnam ( 22 million metric tons), then Russia and Brazil with 21 million metric tons. Further, India, Australia, the United States and Greenland's individual reserves exceed 1 million metric tons.

## 2.2 REES applications

The wide applications of rare earths in traditional sectors, including metallurgy, petroleum, textiles and agriculture, stem from REEs specific and diverse properties such as luminescence, hydrogen storage, high thermal stability, electric conductivity, magnetic, and optical properties [9, 8]. Their unique chemical, electrical, magnetic and optical properties have led to a growing use of the minerals in high-tech industry [87]. Their applications include minor and major components in permanent magnets, high-temperature superconducting magnets, wires, and cables. REEs are present in many everyday technologies, for instance, all of them are used in flat-panel TVs [9] and several compounds of REEs are used in smart batteries. Similarly, hybrid cars, wind turbines, compact fluorescent lights, mobile phones, and disc drives also contain REEs. The use of REEs in modern technologies has grown because their properties enable serious technical advantages such as performing at reduced energy consumption, greater efficiency, miniaturization, speed, durability and thermal stability [9]. Some products require a single element of rare earths, while others require a mixture of REEs. For instance, cerium is used alone as a polishing agent for glass, contrary to neodymium-praseodymium alloy used in permanent magnets or europium-terbium-yttrium combination in REEs phosphors. REEs are always used in small quantities, and some individual elements are critical to the production of one

particular technology. For example, erbium is the only element with the optical properties necessary to make laser repeaters work [87]. Due to the growing use of REEs in clean technology, these minerals have become critical resources for the energy transition. Similarly, their use in the defence sector has increased their economic criticality.

## **2.3 REEs production**

The current legal annual global production of rare earth oxide is estimated at 280 000 tons [16], of which China accounts for 60%, USA 16%, Myanmar 9%, Australia 8% and 3% for Thailand. The production of rare earths includes exploration, extraction and all following processing stages (beneficiation, chemical treatment, separation, purification and refining) [77]. Extraction, concentration and processing are often specific to a deposit type or even single deposit resources. The extraction process is influenced by both cost considerations and requirements of technical performance. REEs processing is expensive due to low concentration of rare earths ore deposits, chemical similarities of elements as well as high-purity single-element products required for the high-tech industry. The mining of individual elements is economically inefficient ; hence it is not possible to selectively target just one single element of the REEs family. As previously stated, the processing cost for bastnaesite and monazite deposits largely exceeds the processing cost for ion adsorption clays. In addition, the exploitation of certain deposits generates radioactive waste, which must be managed at a high cost.

## **2.4 Critical raw minerals**

### **2.4.1 Criticality**

There is no single definition for critical minerals, contrary to the concept of strategic minerals associated with the availability of certain materials used in the military and industry in times of war or national emergency [18]. Despite the lack of a common definition, [38] characterizes a critical mineral as a “valuable constituent element of a mineral commodity that is subject to the risk of supply disruption and which serves a purpose deemed as important based on the evaluators’ perspective”. Accordingly, a mineral is critical when it has an essential function and has few or no substitutes. Besides specific needs and high demand, minerals are critical if there is a high probability of supply risk, mostly due to geologic, technical, political or economic factors. The notion of criticality also refers to the question: to whom is a mineral critical? The answer is an industry but more broadly, an entire economy. Therefore, countries, academics, and



private sectors assess mineral criticality according to their definition and criteria. Several countries have developed a List of Critical Raw materials for the last decade, including the United States, the European Union, Japan, Australia, the United Kingdom, and India [14, 33, 56, 35]. These lists generally evaluate criticality through two dimensions: supply risk and economic importance. For each dimension, indexes and indicators are developed to assess the criticality of minerals or groups of minerals, and the results are then presented in a matrix. Lists of critical minerals are revised frequently since criticality may evolve according to market dynamics, technological changes and political decisions. A third dimension of the analysis exists; it considers the environmental hazard and damage of the mining activities [59]. The criticality of rare earths is among the highest concerning the three dimensions. Figure 3 shows the results of the European Commission’s 2023 criticality assessment. The matrix is quite similar to the criticality matrix from U.S. Department of Energy(Figure 4).It is apparent from the European Commission matrix that HREEs and LREEs are markedly above the criticality threshold. Both have a high supply risk, but LREEs have greater economic importance. The economic importance of REEs has increased since the previous criticality assessment due to the growing use of REEs in permanent magnets application. The lack of substitutes for each individual rare earth for each application also contributes to rare earth’s rising economic importance. Supply risk remains high for REEs since China provides 100% and 85% of the EU’s supply of HREEs and LREEs, respectively. Considering both dimensions, rare earths are among the most critical raw materials. Along with the other minerals needed, such as cobalt, lithium, manganese, and graphite, rare earths are especially important for the energy transition .

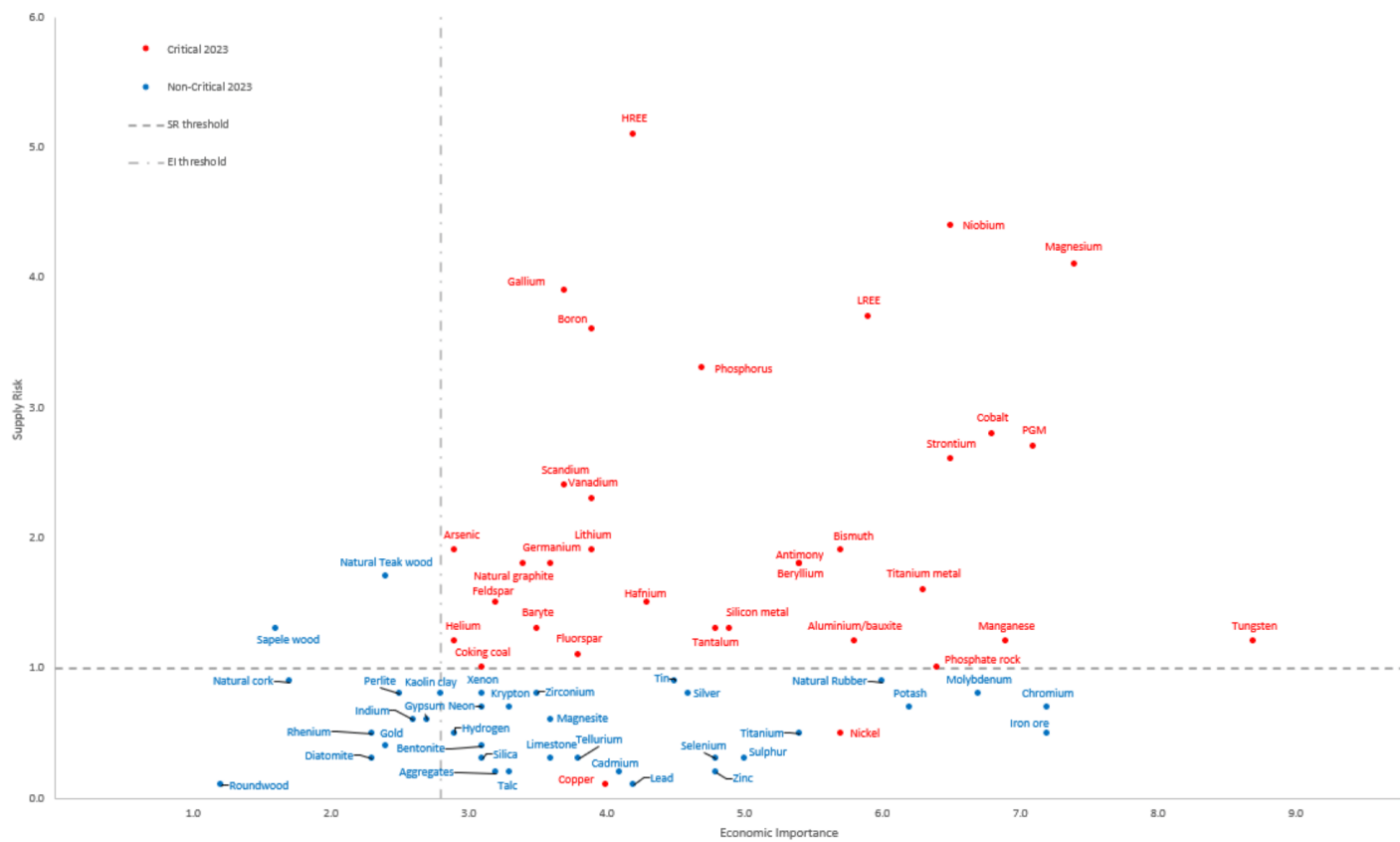


Figure 3: Criticality assessment results, European Commission (2023)

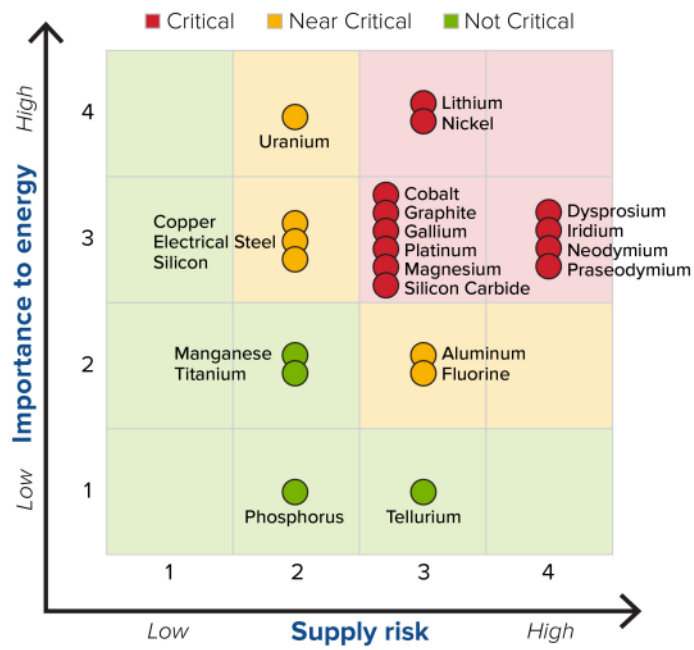


Figure 4: Medium term(2025-2035) criticality matrix, DOE (2023)

### 2.4.2 The geopolitics of Rare earths

One of the most significant current discussions regarding critical minerals and particularly rare earth elements is the geopolitical shift emerging from the energy transition. According to [36], deploying renewables could replace countries' dependence on fossil fuel resources with dependence on mineral resources, creating new relationships between resource-rich countries and others. Regarding REEs dependence, the attention is confined to China's central role in the market and its protectionist measures [40, 41, 57, 58, 47, 75, 28]. The general conclusion of these studies is that countries reliant on China's rare earths would have to reshape resource policies and forge new alliances to reduce their dependence on China's resources and avoid putting their economies at risk of supply disruption.

## 3 Rare Earth and the Energy Transition

### 3.1 Energy transition

Under the Paris Agreement, 175 nations reinforced the global response to climate change to limit the increase of global warming temperatures to under 2°C above pre-industrial levels. To reach this goal, they have shaped national and international policies built on two pillars: mitigation and adaptation. Mitigation is carried out through decarbonisation roadmaps, such as the large-scale development of low-carbon energy as a substitute for fossil fuel energy [31, 70]. Specifically through the European Green Deal, The Anti-Inflation Act, the Canadian Net-Zero Emissions Accountability Act, and the Carbon neutrality target before 2060. These policies set the pathway for an energy transition. This is defined by the International Renewable Energy Agency (IRENA) as a 'pathway toward the transformation of the global energy sector from fossil-based to zero-carbon by the second half of this century' [30]. Higher energy efficiency and a higher share of renewable energy are the two pillars of this energy transition [29]. Rare earths contribute to both pillars; first, their unique properties allow for a gain in efficiency, and second, they are key components of renewable energy technologies. The global development of renewable energy is rapidly increasing, intending to reach net zero emissions compared with the pre-industrial era [94, 89, 53]. The share of renewables in total electricity generation should globally increase from 29% in 2020 to over 60% in 2030 and to 88% in 2050 [44, 43]. Solar PV and wind will become the leading sources of electricity before 2030. To achieve these results, annual wind and solar capacity additions between 2020 and 2050 will be five times higher than the average addition over the last three years [44]. Likewise, the transformation of the transport sector, notably the development of electric vehicles, will

also contribute to emission reduction. In a Net Zero Emission scenario, electricity becomes the principal fuel in transport by 2040 [44].

### **3.1.1 REEs and minerals critical for the energy transition**

Renewable energy technologies are more mineral intensive than current energy resources. Consequently, transforming the electricity sector requires huge volumes of raw materials; some are critical raw materials. In a scenario that meets the Paris Agreement goals, the total mineral demand for clean energy will quadruple by 2040 [43]. In this scenario, minerals demand is driven by the energy and transport sector. Clean energy technologies' share of total demand will rise to over 40% for rare earth elements and copper, 60- 70% for nickel and cobalt, and almost 90% for lithium between 2020 and 2040 [43]. Although these minerals are already considered critical, their criticality might increase due to their expected economic importance in the energy sector and their high supply risk stemming from their production concentration in certain regions. Rare earths are critical to the energy transition through their use in permanent magnets. Permanent magnets transform mechanical energy into electrical energy and operate in wind turbine generators and EV motors. Neodymium, praseodymium, dysprosium and terbium are the four elements included in the production of permanent magnets called Neodymium-iron-boron magnets (NdFeB). Neodymium and praseodymium are the main components of these magnets as they contribute to the magnetic strength, while dysprosium and, to a lesser extent, terbium are added in smaller quantities to improve resistance to demagnetisation, particularly at high temperatures. Neodymium and praseodymium usually co-exist in mineral deposits due to their similar properties. That's why Nd-Pr alloy is used in permanent magnets. However, dysprosium is far less abundant than other rare earth elements, and its low availability may hinder the development of high-temperature NdFeB magnets for EVs and wind turbines [6, 22]. In 2020, some 29-35% of all REEs were used for permanent magnets [30].

### **3.1.2 Wind turbines**

In 2020, around 10% of permanent magnets were used for wind turbines, notably offshore and Chinese onshore turbines [30]. Permanent magnets incorporate 29-32% of Neodymium- praseodymium and 3-6% of dysprosium [64]. However, the amount of permanent magnets differs according to the type of wind turbine. There are two technical designs of wind turbines in onshore and offshore applications: gearbox (GB) and direct drive (DD). Gearbox turbines exist with mid-speed drive trains and high-speed drive

trains. The mid-speed gearbox consists of turbines with moderate permanent magnet content (GB – PMSG), while high-speed drives include a design with low permanent magnet content and another one with no permanent magnet, called a double-fed induction generator (GB - DFIG). Direct drive turbines offer only a low-speed drive option with two designs: a Permanent Magnet Synchronous Generator (DD-PMSG) and an Electrically Excited Synchronous Generator (DD-EESG) as shown in Figure 5. Permanent magnet use in wind turbines allows for smaller and lighter designs for the gearbox configuration [64]. In offshore sites, turbines are taller and larger, therefore DD-PMSG are preferred due to their lighter and more efficient attributes, as well as lower maintenance costs. In a comparison between DFIG and PMSG turbines, [60] has shown that, for a hypothetical 100 turbine site 40km offshore, the PMG turbine has a Cost of Energy that is £2.31/MWh lower than that of DFIG one. In general, PMSG wind turbines are more efficient than other ones, specifically for offshore use. This greater efficiency is partly due to rare earth elements' strong magnetic properties and light weight. Currently, GB-DFIGs dominate the market for onshore applications. However, DD-PMSGs have doubled their market share over the past decade accounting for 10% of the installed turbines in 2010 to 20% in 2020 [43]. The onshore wind capacity is set to triple by 2050, with PMSGs remaining an important part of the onshore market. In the offshore market, PMSGs prevail over GB-DFIGs. The global offshore wind market is expected to grow by over 13% annually by 2040 [42], reinforcing the development of DD-PMSGs in offshore sites since they present greater advantages for offshore applications.

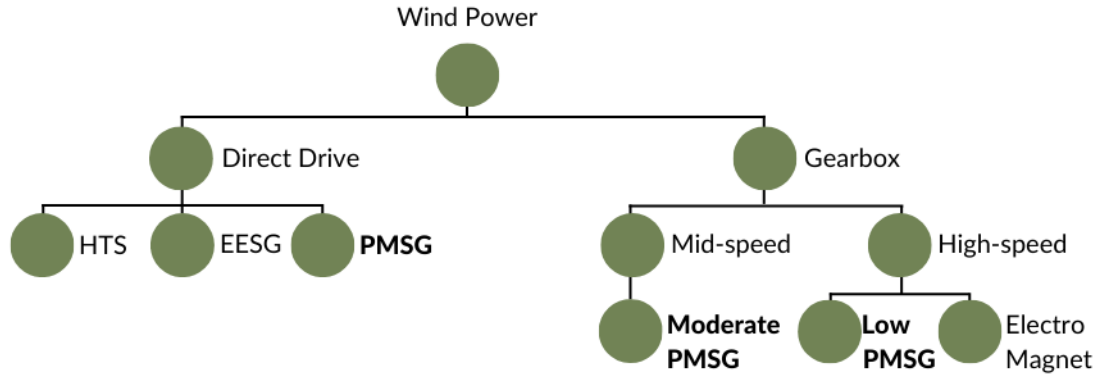


Figure 5: Wind sub-technologies subdivided according to their drivetrain configuration. Source: Adapted from Manberger and Stenqvist (2018)

| Material          | Range  | DD-EESG | DD-PMSG | GB-PMSG | GB-DFIG |
|-------------------|--------|---------|---------|---------|---------|
| Dysprosium (Dy)   | 2-17   | 6       | 17      | 6       | 2       |
| Neodymium (Nd)    | 12-180 | 58      | 180     | 51      | 12      |
| Praseodymium (Pr) | 0-35   | 9       | 35      | 4       | 0       |

Figure 6: Rare earth usage estimates in t/GW for different wind turbine types. Source: Carrara et al., 2020

Two main scenarios are anticipated regarding the development of the different wind turbine types in the decades to come. In a scenario based on current policies and Paris Agreement goals, PMSG wind turbines will represent 95% of offshore wind turbines in 2040, whereas this share is 30% for onshore turbines[43]. These projections correspond with the fast and large-scale development of wind capacity and the need to gain efficiency to meet the Paris Agreement goals. However, these projections assume that the supply of critical raw materials, notably rare earths, would meet the demand for permanent magnet production. In a rare earths constraint supply scenario, manufacturers would switch to hybrid designs with fewer rare earths or wind turbine models without REEs components. Therefore, according to [43], the share of PMSG wind turbines would fall under 20% for the onshore market and remain around 90% in the offshore market but with greater use of REE-free magnets. This would result in a 15% decrease in praseodymium demand and 32% decrease in dysprosium demand by 2040 [43]. These scenarios will depend on various factors, such as mine development time frame, price variation, manufacturer technology choices, and innovation development. Those conclusions are drawn on current market development and the feasibility of short-term predictions. In contrast, [24] has developed three different demand scenarios for wind turbines market shares taking into account the future penetration of new technologies. As can be seen from Figure 7, PMSG offshore application remains between 70-80% in medium and high-demand scenarios, whereas it drops to 40% in the low-demand scenario.

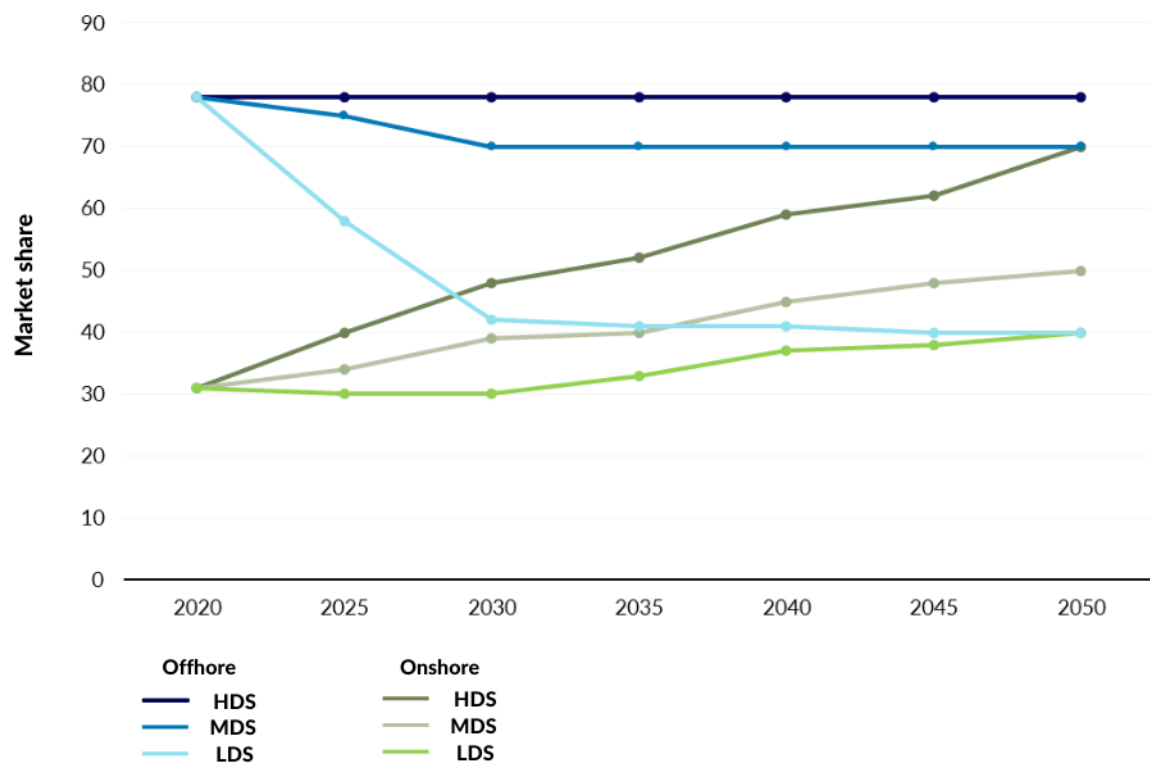


Figure 7: Scenarios for the use of permanent magnets in wind turbines. Notes: HDS; LDS and MDS are for High, Low and Mid Demand Scenarios. Sources: Adapted from Carrara et al. (2020).



### 3.1.3 Electrical Vehicles

Permanent magnets used in electric vehicles (EVs) and hybrid vehicles (HVs) are different from the ones used in wind turbines. Although they contain a large amount of neodymium and praseodymium, dysprosium is sometimes replaced by terbium. Rare earth elements can also be found in EV's NiMH batteries along with lanthanum, cerium and neodymium used for hydrogen storage, while europium and yttrium operate in LEDs. The average amount of REEs contained in EVs are 580-870g lanthanum, 1226-821 g cerium, 189-135g praseodymium, 649-555g de neodymium and 149-71g dysprosium [88]. EVs incorporate more REEs than conventional vehicles. Conventional vehicles have between 17-111g of REEs compared to 2240-3200g in EVs[88]. There are two types of motors for EVs, Permanent-magnet synchronous motors (PM) and asynchronous induction motors. Permanent magnets optimise the power-to-weight ratio in motors, allowing for lighter and more efficient vehicles. Rare earth elements largely contribute to the higher efficiency of PM motors, even though some permanent magnets do not use REEs and are as such less coercive [43]. Currently, the market share of EVs using permanent magnets reaches 90% [24]. This market is expected to grow at historical rates in the years to come since e-mobility is one of the main policy pillars to mitigate Co2 emissions by 2050 [2, 13, 1]. By 2025, the number of EVs on the road should be 77 million, with the EVs fleet representing 13% of all vehicles in China and 8% in Europe [17]. In a 2°C scenario the global EV fleet might be as high as 970 million by 2050 [37]. In such a scenario, the demand for rare earth elements would be driven by the automotive sector since the deployment of EV in the world will necessitate large volumes of REEs [24]. According to [82], demand for REEs in permanent magnet applications for wind and EVs will increase between 3.7% and 12.5% annually, depending on the scenarios and the projection method used. However, the development of electric mobility requires a large amount of critical raw materials. Therefore the deployment of EVs is vulnerable to the supply of critical minerals such as rare earth, lithium, nickel or cobalt [10]. The supply of dysprosium is of particular concern for the future production of permanent magnets owing to its low crustal abundance concentration and China's monopoly on heavy rare earth mining and processing [10, 24]. At the current exploitation trend, dysprosium supply cannot meet future demand for EV motor production. [39, 10, 22]. EV motors and wind turbine generators are expected to be the largest end-use of dysprosium in the years ahead since dysprosium doesn't have other significant applications. According to [15] a large proportion of dysprosium produced in China was derived from illegal mining, and the government's actions to curb this production resulted in a decrease in dysprosium supply. In addition, the fast development of e-mobility in China will undoubtedly increase its domestic demand for dysprosium. Therefore, a dysprosium shortage might occur if no alternative supplies are developed. One solution may lie in the development of the Browns Range mine in Australia. Production from this

mine would be sufficient to produce as high as 2.7 million motors for EVs [15]. Another issue regarding the supply of rare earth is co-mining, since rare earth elements cannot be mined individually, an increase in production for one element proportionally increased the volume of other rare earths in the market. This led to an oversupply of co-mined elements and a price fall in the rare earths market [10, 22].

## 4 The Rare Earth market

### 4.1 The Central role of China

Initially, the United States was the world's first supplier of REEs. Starting in the 1950s, the Mountain Pass deposit provided the world with REEs. The country was also the leader in rare earths applications and innovation. China's interest in rare earths emerged in the 1960s when it developed the mining of non-ferrous metals in the Baotou region, setting up the home of large factories that process coal, steel, and rare earth metals [50]. The United States leading position in the market rapidly declined from 2002 when Mountain Pass closed after severe environmental problems and the emergence of competitive Chinese producers. Progressively, mines and processing facilities in the States were acquired by conglomerates, including several Chinese entities. REEs companies relocated their operations to China. For instance General Motors, delocalised its MagnaQuench division, which is specialised in minerals processing, after being bought by a Chinese consortium [49, 74]. China used its low environmental standards and cheap labour to capture market shares and gain a dominant position in the market. The Chinese State has supported the development of a competitive rare earths upstream industry, mainly through the Raw Materials Office of the Ministry of Industry and Information Technology (MIIT), and the Ministry of Commerce. One essential measure of China's raw material trade policy is to introduce export regulations. In the rare earth market, export quotas and export licensing have been in place since 1999 [50]. The country has progressively reduced its exportation quotas with the intention of attracting foreign companies to set up factories in China, share their know-how and develop manufacturing of products with a higher added value [74]. China has secured an absolute monopoly in rare earth production, from mining to processing. In 2005, the country accounted for 95 % of global REEs mining. However, in 2010 the so-called Rare Earth crisis led to global concerns regarding China's monopoly and marked a complete change in the rare earths market. The crisis emerged following a diplomatic incident between China and Japan over a maritime dispute, and it was reported that China temporarily ceased REEs exports to Japan. Although China did not issue an official statement, the embargo toward Japan was de facto, according to

Japanese companies [50]. The supply disruption led to insecurity in the market, and rare earths prices dramatically spiked. Neodymium and praseodymium prices doubled in less than a year [16]. This episode contributed to the reduction in Western country sourcing from China, resulting in a Rare Earths exploration boom to develop a REEs supply chain outside the country [63]. After 2010, several rare earth projects emerged and mines such as Mountain Pass resumed activities. Although China lost market shares over the years, it still accounts for 60% of REEs mining and 90% of its processing. In 2022, the total value of REEs compound and alloy exports from China exceeded USD 1 billion, whereas the USA's total export value was USD 570 million and Japan's USD 272 million[5]. China also pursued its ambitions to develop REEs end-products with higher value-added, and it did so with permanent magnets. In a decade, China overtook Japan and became the leader in permanent magnets exports, multiplying by eight its export value [57]. China's central role in the rare earths market is also due to its geological particularities, as it hosts the world's biggest reserve of REEs. Its ionic clay deposit is enriched in HREE, and its economic exploitation is economically viable due to low-cost in-situ and heap-leaching [55]. The country capitalized on this deposit to become a leader in HREEs extraction and processing. As of today, the country owns the only HREEs processing facilities. To secure this monopoly, Chinese companies started outsourcing rare earths mining in Myanmar's Kachin region in a similar HREE-enriched ionic clay deposit. Through shareholding and joint ventures, Chinese companies are also involved in several other REEs projects worldwide (e.g., Tanzania, Madagascar, and Australia). With its major implication in each step of the REEs supply chain, the country has become an unavoidable actor in the REEs market, similarly to its position in other minerals markets (see Figure 8 and Figure 9). In short, China remains the biggest global supplier of raw and processed REEs, and through Chinese companies' involvement in REEs projects abroad, China maintains its market power.

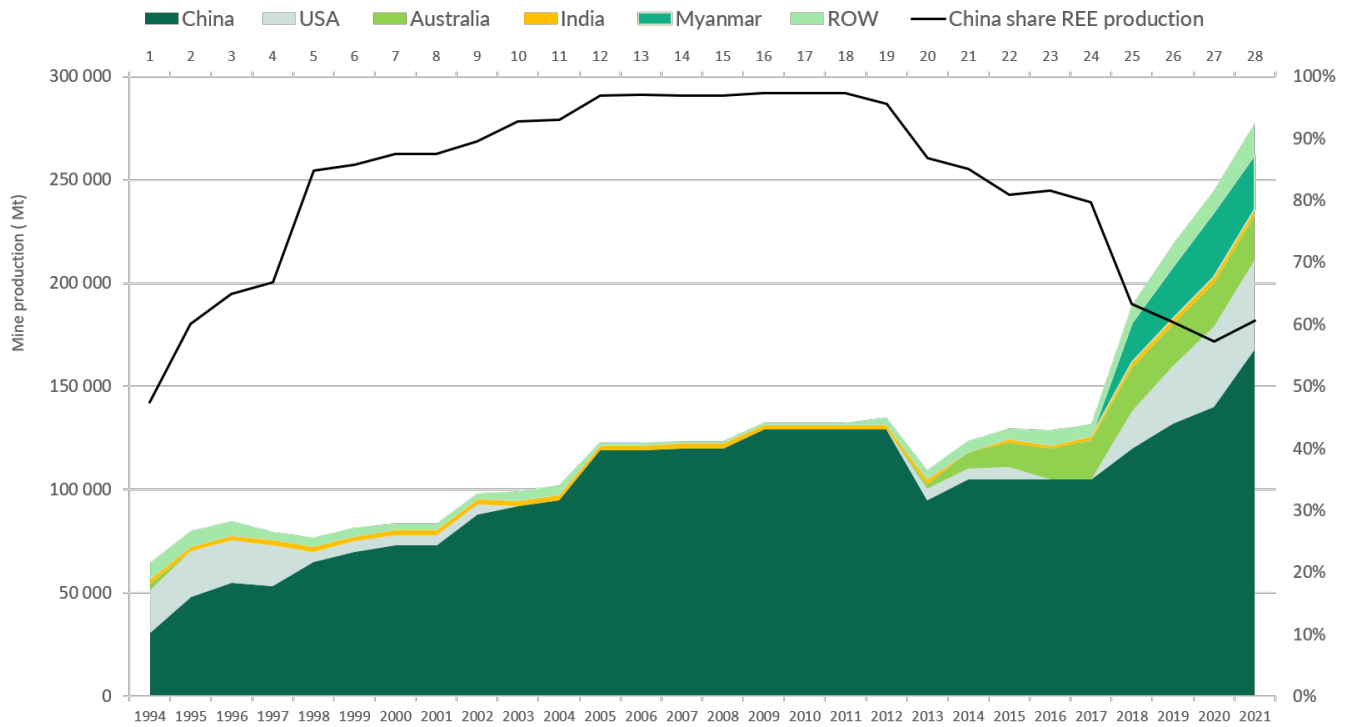


Figure 8: Mine production of Rare Earth Oxide, USGS(2022)

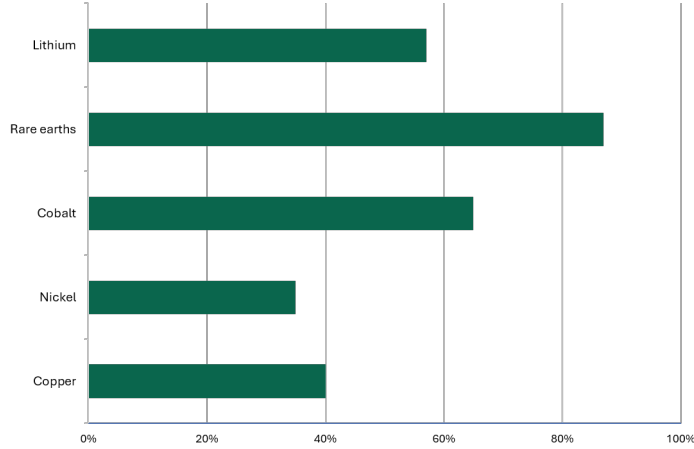


Figure 9: Share of China for minerals processing, IEA (2019)

## 4.2 REEs market

Although the dominant position of China is one main feature of the market, other elements characterise the REEs market. While other raw materials, like copper and gold, are traded in a transparent commodity exchange market like the London Metals Exchange, there is no such market for REEs. They are commonly traded in over-the-counter (OTC) markets. The buyers and sellers are matched through brokers or trading platforms such as Metal Pages, Asian Metal and China Rare Earth. Bilateral agreements and offtakes are concluded in an opaque manner, which makes it harder to estimate exchanged volumes and values. The market's opacity is reinforced by uncertainty regarding supply, demand, resources and reserves, production capacities and cost, prices, and stockpiling size [51]. The resources and reserves of rare earths are not precisely known. Although some countries, including China, do not publish detailed information regarding their resources, the USGS does provide global data on REEs reserves, resources and productions, based on national publications of geological data. Uncertainties regarding production remain since production costs vary according to the deposit type and available technologies. Illegal mining and processing of rare earths in China contribute to uncertainties regarding the total volume produced. Several mining operations operate off the books in Southern China, estimated to represent half the global production of heavy rare earth [61, 74], and around 15-20% of all rare earth elements. The production of illegal mines also lower prices; therefore China's policies to curb illegal mining have an impact on global prices [57]. Historically, rare earth prices have been relatively low, driven by China's considerable resources and its competitive prices. However, during the REE crisis, prices dramatically increased, up until 2011 they were nearly 11 times higher than in 2009 [16].

According to [57] rare earths prices are dependant and volatile on Chinese actions. Price volatility caused uncertainties for consumer industries, and price peaks have a dramatic impact on those industries. IT companies in the United States experienced a reduction in their gross margins as a result of price increases in 2011. [67]. Price volatility also hindered the development of rare earth mines outside China. The stockpiling of REEs, notably heavy rare earths by China, the United States and Japan contribute to price volatility and market uncertainties. The REEs market is also characterised by elastic demand and inelastic supply. There is a different time scale between the exploration of a deposit and the available final raw material on the market. Exploration activities are followed by a preliminary economic assessment, feasibility study, the allowance of an exploitation license, the construction of the mine and low-scale production development to reach large-scale production eventually. This process can take 5 to 15 years. This results in a relatively inelastic supply of REEs in the short term and an elastic demand driven by constantly evolving high-tech industries, where future rare earth applications remain unknown, so is future demand.

## 5 Challenges

As we have seen the energy transition is putting pressure on the extraction of critical minerals required in low-carbon technologies. Rare earths used in wind turbines and EVs are driving the demand, whereas the supply is constrained by production concentration in China and the country’s protective resource policy. This current situation raises several issues regarding the availability of the resource for the development of renewables and electric mobility. We have identified four challenges of rare earths supply for the energy transition, namely the substitution of the minerals in clean technologies, the recycling of REEs from end-of-life products and mining waste, the diversification of the supply and the difficult establishment of a supply chain outside China, and the environmental and social impact of REEs production. These four challenges are further developed in the following section as well as relevant policy implications.

### 5.1 Substitution

The critical availability of rare earths encourages industries to search for alternatives to rare earths in manufacturing high-technology products. However, the direct substitution of REEs by another chemical element is rather unfeasible since no element possesses the same chemical properties as rare earths. Effective substitution is obtained when

an element replaces the critical element with a less critical or a more abundant one while still maintaining its intended purpose [12, 11]. This direct substitution of elements cannot be achieved between REEs and other elements; only the elements of the rare earth family share the same chemical properties and therefore fulfil the same usage without reducing the final efficacy. For instance, dysprosium is sometimes replaced by terbium in the manufacturing of NdFeB. Currently, all rare earth elements are critical, hence the substitution between elements from the rare earth family does not reduce the critical risk. For this reason, manufacturers essentially focus on reducing the amount of REEs in their products and developing alternative manufacturing for their products, named "technology-for-element substitution" [62]. Yet, by reducing the quantity of rare earths in products such as permanent magnets, industries accept a relative performance loss for their final products.

### 5.1.1 Automotive sector

In the automotive sector, we can observe a decreasing trend in the use of REEs in hybrid and electric vehicles. One solution to reduce the amount of REEs is to use a hybrid magnet structure by replacing a portion of the RE-magnet with ferrite materials [65]. For instance, the motor of the BMW i3 is made with a "hybrid" structure that uses around half the REE compared to regular EVs [43]. Another option is to use alternative magnets, whether with low REEs content like samarium-cobalt-ferrite magnets or without REEs like aluminium-nickel-cobalt and ferrite magnets. Those magnets present advantages, the samarium-cobalt magnet can withstand higher temperatures than NdFeB [86], likewise, ferrite magnets are the least expensive permanent magnet [78]. Nevertheless, those magnets have lower magnetic strength, and a lower ability to resist demagnetisation once magnetised [86]. They also contain other critical raw materials such as cobalt. In this search for alternatives to rare earths, the automotive sector has designed free-REEs motors for electric vehicles. The induction motor, for instance, does not use rare earth elements, even though it requires a large quantity of copper (11-24kg per motor), some manufacturers have replaced it with aluminium, a less critical raw material [43]. Another promising alternative is the squirrel cage induction asynchronous motor that is already used in several EVs including TeslaS-2014, TazzariZero, Mercedes-Benz B-Class Electric Drive, Mahindra e2o, and ToyotaRAV4 [68]. This system offers a low-cost and robust alternative to permanent magnet synchronous motors. Similarly, switch reluctance motors are relatively cheap, easy to manufacture and resist high-temperature [68]. However, they are still in the early stage of development [68, 43]. Thus, the global trend in the automotive sector is to scale down or eliminate the use of rare earth permanent magnets in EV motors. Among the alternatives noted earlier, ferrite magnets and induction motors

seem to be preferred by car manufacturers.

### 5.1.2 Wind power sector

In much the same way, in the wind power sector, the global trend is the reduction of REEs in wind turbine generators. By improving the material efficiency, manufacturers can reduce the use of REEs, this can be achieved by improving the permanent magnet design or lowering the working temperature to reduce the use of high-temperature resistant elements like terbium and dysprosium [64]. The advancement in the designing of permanent magnets is also leading to a reduction in the volume of praseodymium and neodymium used in wind turbines. As for permanent magnets in EVs, the direct substitution of REEs in permanent magnets is not the focus of ongoing research, since no substitute for REEs exists. Thus, research and development focus on improving the capacities of existing magnets such as ferrite or aluminium-based magnets [64]. [66] found that ferrite magnets can be an attractive substitute to the REEs magnets, with higher average efficiency and a similar cost in the case of direct-drive wind turbines. The main strategy of the wind power industry is however to switch to alternatives to PMSG that already exist. The doubly-fed induction generator is a rare earth-free type of wind turbine based on an electromagnet. Its low manufacturing cost is its main advantage; however, this generator remains less efficient than REE-permanent magnets and requires higher maintenance costs. Among other alternatives, there are electrically excited synchronous generators (EESG) in direct-drive turbines and squirrel-cage induction generators. High-temperature superconductors might become future alternatives to permanent magnets, however, they are still in the early development stage [64, 43].

## 5.2 Diversifying

Countries' overreliance on China's rare earths, including raw minerals and processed minerals, presents a risk for downstream industries that use REEs. Any disturbance in the exports of raw minerals has an impact on the other segment of the value chain. In the rare earths case, China is also a leading actor in the export of manufactured products with REEs including permanent magnets that are critical to low-carbon technologies. In addition to weakening industries, this dependence also may hinder the energy transition. The 2010 REEs crisis deeply changed the rare earth market. Not only did the price peak trigger an exploration boom from junior and senior companies leading to dozens of REE projects, this event was also a turning point in countries' resource policies. The diversification of rare earth supply became crucial to secure global supply chains, and



different strategies have been adopted. To further analyse critical raw material-securing strategies, resource-rich countries and resource-poor countries will be treated separately. Among rare earth-rich countries, Australia and the United States have pursued similar strategies. Those countries had produced rare earths prior to closing mines in the 2000s due to environmental concerns, little public acceptance and inability to compete with China. Hence, both countries had infrastructures, know-how and widely developed mining industries to exploit rare earths on national soil. Consequently, private company Molycorp resumed rare earth mining in Mountain Pass, California in 2017 and increased the quantities of rare earth mined in the subsequent years. The Mountain Pass production doubled between 2018 and 2021, from 18,000 tons of TREO (total rare earths oxide) to 41,000 tons (USGS). In Australia, Lynas company resumed mining at Mound Weld, and Northern Minerals launched the Brown Range Project in the northern region of the country with the aim of becoming a significant producer of dysprosium, a heavy rare earth that is currently only produced in China. Regarding resource-rich countries without a previous history of rare earth mining, the ambition was to explore deposits and carry out economic assessments of future rare earth projects. Globally, an exploration boom occurred after the 2010 crisis involving mining companies willing to invest revenues from producing mines into new mining projects and junior companies attracted by “high risk / high reward” projects [63]. For those countries, however, the mining mineral strategies largely differ. Developed resource-rich countries such as Sweden and Canada rely on private national stakeholders to develop rare earth projects whereas developing resource-rich countries including South Africa, Tanzania, Burundi, Vietnam, Thailand and Malaysia seek direct foreign investments. Canada for instance has built on its advanced mining industry to develop its first national rare earth project, the Nechalacho Project. In Sweden, the recent exploration of the Per Geijer deposit reported a resource of rare earth evaluated at one million tons <sup>1</sup>. The Swedish authorities should deliver an exploitation licence to the LKAB companies in 2023, permitting the deposit to become the first rare earth mine in Europe. Despite a profound decline in the mining industry in Europe after the closing of coal mines, the European Union has decided to support non-energy minerals mining in Europe. The EURORARE project and the European Rare Earth Competency Network were established by the European Union to improve REEs supply security by evaluating domestic resources, developing exploitation technology as well as creating a network of qualified engineers and scientists (EURORARE, ERCON). In contrast, developing resource-rich countries cannot rely on a strong and developed mining industry; therefore their national strategies aimed at attracting direct foreign investment, like supporting joint ventures and allowing exploitation permits to foreign firms to develop domestic rare earth mining [3]. In particular, African countries have received a huge amount of direct

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<sup>1</sup><https://lkab.com/en/press/europes-largest-deposit-of-rare-earth-metals-is-located-in-the-kiruna-area/>, Accessed June 1, 2023

foreign investment from China in the mining sector, specifically for critical raw materials such as cobalt, copper and rare earths [23]. Malaysian and Vietnamese rare earth plants are respectively owned by Australian and Japanese firms. Resource-poor countries have also developed mineral strategies to secure the supply of critical minerals, notably to support national planning in the green transition. The main strategy consists of bilateral agreements between producer countries and consumer countries (e.g Korea and Canada, Brazil and Germany, France and Mongolia, Vietnam and Japan). Cooperation between countries is at the centre of the global willingness to secure resilient critical raw material supply chains. Australia, Canada, Finland, France, Germany, Japan, the Republic of Korea, Sweden, the United Kingdom, the United States, and the European Commission have established a Mineral Security Partnership to “ensure that critical minerals are produced, processed, and recycled in a manner that supports the ability of countries to realize the full economic development benefit of their geological endowments”<sup>2</sup>. Japan was the first to secure rare earths supply outside China as high-end product with REEs represents 22% of Japan’s total export value [72]. The country created the Japan Oil, Gas and Metals National Corporation (JOGMEG), an independent administrative institution responsible for resource stockpiling of 34 metals, including rare earths. Through this entity, Japan has invested in rare earths companies such as Lynas and rare earth projects around the world. In addition, Japanese high-tech and automotive companies have several joint ventures with rare earth producer companies. Diversification strategies are not only focused on the raw materials but also on the downstream industry. Canada’s strategy consists of intensifying the mining of critical raw minerals as well as reinforcing the associated value chain. Two of the three value chains identified as having high potential for national integration are clean energies including wind turbines and EVs, and advanced manufacturing inputs and materials including permanent magnets [4]. This strategy will be supported by government investment and tax reduction for mining, processing and manufacturing projects across the country. The United States follows a similar strategy embodied in the Anti-Inflation Act. Additionally, the rare earth supply chain diversification planning is also in the hands of the Department of Energy and Department of Defence, outlining the strategic importance of the resource. Countries from the European Union have developed a set of goals to ensure the securing of critical raw materials for the energy transition, through the European Critical Raw Material Act (CRMA). This act plans to establish strategic raw materials partnerships with countries with important reserves, pursue a predictable legal framework for trade and investment in REEs in Australia, and support investment in REEs mining/processing in Ukraine. As for Canada and USA, the diversification strategy includes all value chain segments. The European Union has set the following goals : 10% of EU’s annual consumption for extraction, 40% of the EU’s annual

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<sup>2</sup>Retrieved from <https://www.state.gov/minerals-security-partnership/>, Accessed June 1, 2023

consumption for processing, and 15% of the EU’s annual consumption for recycling have to be produced within the European Union. In addition, no more than 65% of the Union’s annual consumption of each strategic raw material at any relevant stage of processing can come from a single third country. Diversification strategies might be limited by China’s control over the rare earth market. Developing an alternative value chain means changing the structure of the market and facing Chinese competition. Chinese companies are still present in each segment of the market, and any rare earth produced today has to pass through China. Moreover, the rare earth industry necessitates high investment associated with high risk, as the economic viability of deposits is rare.

### 5.3 Recycling

The recycling of REEs is a solution to increase the supply of REEs, secondary sources of REEs could represent an important proportion of the future supply of REEs. There are two types of recycling to be considered: pre-consumer recycling involving recycling performed on manufacturing scrap and post-consumer recycling which means recycling end-of-life products. The latter has a bigger potential as a tremendous amount of technologies with REEs contents have already been produced - electronic wastes including nickel-metal hydride batteries, hard drives from laptops and desktop computers, cellular phones, and speakers [27]. The so-called “urban mines” represent a potential for recycling of REEs and second-life use in green technologies. Urban mining is when wastes that typically end up in landfills are instead processed for recovery of contained materials [27]. As of today, less than 1% of REEs are recycled - the lowest proportion of recycled minerals among the critical minerals for the energy transition [43]. The main reason for this low rate is quality loss, available recycling technologies, low prices for REEs from primary resources, and the long useful life period of REEs bearing products. However, many products like permanent magnets, batteries, auto catalysts, and phosphors in displays and lighting are applications where recycling may be economically viable. Feasibility will depend on the composition of REEs in the products, how challenging collection and sorting of those products may be, and the viability of recycling technologies to extract REEs at a high yield [27] [27] shows that the large volume of many waste materials would provide a large quantity of REEs to meet global demand, even with low yields. Post-consumer recycling consists of three steps: collection, pre-processing and end-processing. There are three main techniques to recover REEs from end-of-life products: the mechanical technique which usually consisting of grinding, sieving and bed elutriation [79], the hydrometallurgical where REEs bearing alloys are dissolved in large amounts by mineral acids or microorganisms and pyrometallurgical techniques that use very high temperatures to recover metals [62].

### 5.3.1 NiMH batteries

The large volume of disposable NiMH batteries is a source of REEs. This secondary source of REEs has the potential to increase its supply. Four REEs can be recovered from NiMH batteries, cerium, lanthanum, neodymium and praseodymium and then be reused to produce new REE-products. There is a large available volume of NiMH batteries which is mostly explained by their useful life, being about two to three years [90]. According to [27], NiMH batteries could provide 3.6X the global demand for lanthanum, 2X the demand for cerium, 1.5X for neodymium, and 1.1X demand for praseodymium. The recycling of REEs from NiMH batteries has been developing for a decade. For instance, Solvay, a Belgian-French multinational and the only HREEs separation facility outside China, started its LOOP Project in 2010 <https://urlz.fr/mgid>, Accessed June 1, 2023. The project consists of recycling End-of-life NiMH batteries (La, Ce, Pr, Nd) and low-energy consumption lamps from the Solvay La Rochelle plant's historical loss of yield. This is a collaboration with Umicore that recycles the nickel part of the battery. For the past decade, various techniques have emerged for REE recycling from NiMH batteries [45, 62]. New techniques are promising, including techniques that result in reducing wastes such as water waste and liquid waste [45].

### 5.3.2 NdFeB

NdFeB can be recycled from EV/HEV vehicles, wind turbines and hard disk drives. There is a huge recycling potential of NdFeB from hard disk drives because of existing and efficient collection and huge annual production of 600 million HDDs. Neodymium can be recovered from NdFeB [25]. Similar to NiMH batteries, recycling started in 2010. Hitachi has developed technologies to recycle REEs from HDD motors, air conditioners and other compressors. It has developed machinery to separate and collect RE magnets from end-of-life products and extracted REEs from the magnets using a dry process (meaning no solvents are used)[7]. This technology allows for a cost and liquid waste reduction. Technologies are developing and are promising with high purity in recovered elements (99%), and successful reuse in new magnets (fully circular economy)<sup>3</sup>. According to [92] recycling of NdFeB can meet almost 50% of the demand by 2100. However, recycling and recovery of REEs (Nd, Pr, Dy, Tb) from end-of-life magnets are challenging due to their relatively small sizes. According to [73] model, 22 percent of global light REEs and 23 percent of heavy REEs demand for use in NdFeB magnet production can be met by supply from secondary sources in 2030. The recycling of heavy rare earths may impact the market since primary sources are concentrated in China.

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<sup>3</sup><https://urlz.fr/mgia>, Accessed June 1, 2023

### 5.3.3 Pre-consumer recycling

REEs are also present in secondary coal combustion products such as fly ash, bottom ash, and incinerator ash. Phosphogypsum, coal ash and red mud from aluminium production stand out as promising candidates for recovery due to high concentrations of valuable REEs and sufficient quantities to potentially meet demand. Among the sources of REEs materials that have been studied extensively is coal ash. Coal ash is a by-product of the combustion process in coal power plants and has two main components: fly ash and bottom ash[27]. Rare earths can be recovered from coal fly ashes. The potential is such that the U.S. Department of Energy has initiated programs to examine methods of recovering REEs from coal-related wastes<sup>4</sup>. Currently, there are promising systems to recover REEs from coal ashes that address resource recovery and solid management waste [54] even if these systems are still in the development stage.

## 5.4 Environmental damage

Rare earth element production has a direct impact on the environment along the entire life cycle of rare earths, beginning from the mining and ending at the disposal of REE products. The environmental damage has several forms, including chemical contamination, alteration of soils, gas emissions, soil acidification and water contamination. The chemical damage has been estimated by several studies, for instance, the Chinese Rare Earth Society has evaluated that every ton of rare earth elements produced generates approximately 8.5 kilograms of fluorine and 13 kilograms of flue dust. Additionally, sulfuric acid refining techniques used to produce one ton of rare earth elements generates 9,600 to 12,000 cubic meters of gas laden with flue dust concentrate, hydrofluoric acid, sulphur dioxide, and sulfuric acid. Other estimates indicate that producing one ton of REEs creates 60,000 m<sup>3</sup> of gases mixed with H<sub>2</sub>SO<sub>4</sub> and HF, 200 m<sup>3</sup> of acid water, and 1.4 tons of radioactive waste [46]. Other studies focus on the broader environmental impact of REEs, and several life-cycle assessments (LCA) of rare earth have been performed [52, 93]. The main findings show that Rare earth production is an energy and chemical-intensive process that generates large quantities of mining tailings and results in waste that might be radioactive like thorium and uranium. LCA outlined that the environmental problems caused by REEs production vary according to the production stage and the type of rare earth.

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<sup>4</sup><https://netl.doe.gov/node/12137>, Accessed June 1 2023

#### 5.4.1 Mining

Mining minerals cannot be done without exposing rocks that have not been exposed previously to bacteria, oxygen, water and wind. Chemical and physical alteration caused by these weather forces can lead to environmental contamination. Rare earth element bearing minerals such as monazite, xenotime, and bastnasite can contain low levels of radioactive elements thorium and uranium. The radionuclides, rare earth elements, metals, sulphides, carbonates, and other possible contaminants may be released into the environment at the mine site and refinery [85]. Mining activities also entail alteration of the natural environment, removal of vegetation and topsoil results in changes in topography, and soil compaction reduces infiltration and storm runoff absorbing capacities. This leads to increased frequency and magnitude of flooding and other geological disasters during storm periods. Mining activities also cause permanent loss of ecosystems, soil erosion, air pollution, and biodiversity loss. The rare earth mining in the Ganzhou region has left 302 abandoned mines and 191 million tons of tailing and large-scale deforestation.

#### 5.4.2 Processing

The processing (beneficiation, separation, chemical treatment, reduction) is the stage that creates the largest volume of pollution. REE processing techniques are chemical and energy-intensive. The type of deposits and REEs concentration determine the processing techniques. There are no unique techniques, and each of them may impact the environment. Globally, the Chinese Society of REEs estimates that the completion of refining one ton of rare earth elements generates approximately 75 cubic meters of acidic waste water and about one ton of radioactive waste residue. The environmental damage will also depend on the pollution control the mine operator adopts. During the processing of REEs, chemicals such as acids, alkalis and solvents are used, creating chemical waste and gas emissions. The consumption of water to process REEs also causes water contamination. An additional concern is the impact on the environment from processing waste. In particular, a large amount of tailings is produced in the beneficiation and extraction of bastnasite and monazite concentrates. Tailings of both of these, monazite in particular, contain naturally occurring radionuclides and the release of this to the environment by air, wastewater, and rain leaching can have longer-term health effects on humans and ecosystems of the local environment [52].

### 5.4.3 After mining activities ceased

Even after mining activities ceased, mines still represent an environmental risk. The leaching can cause long-lasting underground water contamination, mine collapses, landslides and soil acidification. Sulphate pollution persists long after mining ceases through exacerbated nutrient pollution of downstream rivers and reservoirs increasing the development of toxic substances for aquatic organisms and plants.

A monazite cracking plant to extract rare earth elements operated in northern Malaysia between 1982 and 1994. During this period waste containing thorium and radium was generated, and various materials and equipment within the plant area became contaminated with thorium[81]. Mitsubishi spent \$100 million to clean radioactive waste leaching in this mine<sup>5</sup>.

## 6 Policy recommendations

### 6.1 Substitution and Recycling

The automotive and wind power sectors have fully acknowledged supply risk from critical minerals used in low-carbon technologies. Companies from those sectors have adapted their product designs and invested in research and development (R&D) to mitigate the supply risk. It results in the availability of permanent magnets without REEs and recycling technologies that recover REEs from secondary sources. Therefore public policies should be framed to support public and private R&D projects which aim to reduce the use of REEs from primary sources and increase REEs supply from secondary sources. These policies might take the form of national subsidies or tax reductions for innovative companies. To guide the design of such policies, it's important to evaluate the domestic amount of industrial waste and end-of-life products that are potential sources of REEs. Additional measures should be taken to ease the recycling process and reduce its cost. First, consumers must be encouraged to recycle their products when they reach end-of-life since any component might be recovered. Second, a full recycling chain must be developed, from collecting end-of-life products to recovering materials. Last, industries themselves should be encouraged to design products which ease the future recycling of their critical key components. Although recycling is a long-term solution to meet the demand of REEs for clean technologies, recycling is unlikely to meet REEs demand in the short term and

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<sup>5</sup><http://www.nytimes.com/2011/03/09/business/energy-environment/09rareside.html>, Accessed June 1, 2023

should be seen as a medium and long-term solution.

## 6.2 Diversifying

The diversification of rare earths supply implies that world resources are identified and measured; therefore, geologic surveys should be done nationally to evaluate REEs resource potentials. In this area, several countries lack expertise and need external support. For instance, the French geological survey bureau signed an agreement with its Congolese counterpart to develop skills, deploy a high-performance Geological Information System, enhance knowledge of the DRC's subsoil and encourage the emergence of responsible mining projects <sup>6</sup>. The research and the target exploration step is one of several that follow every mining project. From this first step to the final step of building an active mine, the probability of success is very low and the timeframe very long. It can take a decade to discover an economic orebody and several additional years to develop a mine. Rare earth projects need financial, legal and political support throughout the full process. The public-private cooperation would be profitable for the development of REEs projects, as noted earlier, high risk and uncertainties are characteristics of the REEs market. Thus, private companies need public support to face market uncertainties. Also, from a mining company declaring its intention to start minerals exploration to the setting up of a mine requires different permits, including mining permits and environmental permits. The process of approving permits needs to be smooth and transparent. Developing domestic REEs projects is part of a broader political context. A set of public policies, including formation, R&D, environmental policies and industrial policies, must back the development of such projects. Regarding mining operations abroad, bilateral agreements and partnerships will enhance collaboration between resource-rich and consumer countries. REEs resource-rich countries have come under the spotlight since the rare earth crisis has awakened interests from foreign companies and governments willing to secure critical minerals supply chains. However, the development of mineral mines supported by foreign companies and governments does not always contribute to the economic and social development of the resource-rich country. Thus, consumer and producer countries must agree on an equitable distribution of benefits to ensure inclusive growth. Moreover, as the mining sector is becoming central in the energy transition, regulations are more than ever needed to ensure responsible and sustainable mineral supply chains. ESG standards would reduce consumers' and stakeholders' concerns about means of production and provenance. The traceability of raw materials is becoming a major concern as demand increases for clean technologies, because illegal mining and mining in conflict-affected countries might

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<sup>6</sup><https://urlz.fr/mgic>, Accessed June 1, 2023



represent a growing share of mineral imports. Recent reports have drawn attention to local governance issues and societal consequences of mining REEs in the borderlands of the Kachin region in Myanmar [19, 71]. In this domain, private and public cooperation is required to shape ESG norms and ensure clear traceability of raw materials.

### 6.3 Environmental and social impact

The environmental impact of REEs production is little known since current studies are based on data from the early production of REEs in Mountain Pass or from China’s mines which have different environmental norms than other mining countries. The development of new REEs project press for available knowledge regarding the environmental impacts of REEs production and existing technology to mitigate environmental risks. Those technologies will help shape environmental standards in the mining industry, which is already moving toward sustainable practices by developing dry-processing techniques that do not necessitate solvents and using data management tools to reduce mining’s environmental impact. Nonetheless, policymakers should work with the mining industry to promote best ESG practices along the REEs value chain. Besides ESG, due diligence is vital, as child labour and minerals from conflict-affected countries are critical risks in the mining industry. Mining companies must ensure that they have taken measures to prevent or mitigate the risk of contributing to conflict and human rights abuses. Setting international standards is key to ensuring a responsible, sustainable and secure supply of minerals for the energy transition. Mining operations might take place near protected areas or in the Indigenous territory, leading to conflict regarding land use. That’s why the involvement of local communities and transparency from the mining industry regarding environmental impacts and restoration of the mine after activities cease are important.

## 7 Conclusion

As we have seen, neodymium, praseodymium, dysprosium, and terbium are the four rare earth elements critical to the energy transition through their application in wind turbine generators and electric vehicle motors. As the world is moving from fossil fuel energy to low-carbon energy, the demand for these minerals is expected to grow substantially over the next decade, and so is the critical mineral supply. However, this article identified four main challenges to the supply and demand of REEs in the energy transition. As a critical mineral, the supply risk is notable for rare earths, partly due to extraction and processing concentration in China. Therefore, substituting REEs is a feasible and already adopted

solution in the automotive and wind sectors to reduce industrial vulnerability to disruption in the supply chain. Moreover, the exploration boom has led to the development of several REEs projects outside China to diversify sourcing. Even if few projects result in active mines or processing plants, new supply chains from extraction to processing of the minerals are emerging in North America and Australia. In addition to an increasing supply of REEs from primary sources, the recycling of REEs from end-of-life products or industrial wastes would increase the global supply of REEs needed in the energy transition in the long term. Despite a current low recycling rate, increasing REEs recycling is a stated objective for several countries. One major concern regarding REEs production remains the environmental impact. Environmental damage associated with REEs extraction and processing put the brakes on REEs projects development. All of these constraints and challenges must be considered by the industrial sectors relying on REEs to manufacture their products. Another challenge that could be investigated is the REEs co-mining. Since REEs are a co-product of each other, an increase in the supply of one REE is translated into an increase in the supply of another, with a risk of oversupply of certain elements. By-products of REEs such as iron, titanium, zirconium and thorium are also to be considered from an industrial point of view, as they could be economically beneficial.

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